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Cosmic-ray laboratory

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EXPERIMENTAL DATA ON NUCLEON-NUCLEON INTERACTIONS AT THE ENERGY OF HUNDREDS OF GEV AND THEIR INTERPRETATION

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EXPERIMENTAL DATA ON NUCLEON-NUCLEON INTERACTIONS AT THE ENERGY OF HUNDREDS OF GEV AND THEIR INTERACTION

The results to be reported here have been obtained at the continuation of studying nucleon-nucleon interactions at hundreds of GeV at the Pamir Station of the USSR Academy of Sciences Physical Institute, 3860 m above the sea-level by a large team of research workers from the cosmic ray laboratory of the Institute.

The first results of this work were presented at the Moscow Cosmic ray Conference, 1959 and the Rochester High Energy Conference, 1960. /1/

The experimental installation in general features remained unchanged (comparing with the first stages of experiment). It consisted of two cloud chambers, one of which was placed into a magnetic field, and "ionization calorimeter" for the determination of the energy of the primary particle. The scheme of the installation is given in Fig.I.

The effective dimensions of the cloud chambers were $90 \times 40 \times 16$ cm^3.

The lithium hydrate (LiH) target was placed between the chambers. The thickness of target was about 0,1 of the range for nuclear interaction.

The "ionization calorimeter" consisted of 8 layers of ionization chambers (altogether 120 ionization chambers) separated by lead and brass filters. The total thickness of the filters was equal to 5,3 units of nuclear interactions.

The following characteristics for each recorded shower can be determined from the obtained results:

1. E_o - from its total energy release (i.e. without any assumption about the symmetry of shower particle distribution in C-system, usually made in experiments by

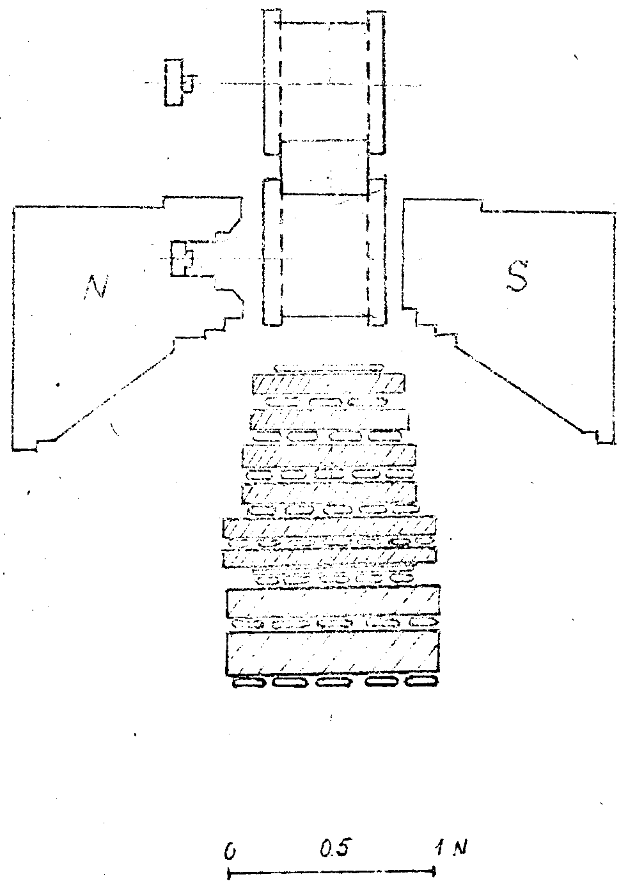

Fig 1

2. The charge of the primary particle (whether the particle which generated the shower charged or neutral).
3. n_s - the number of charged secondary particles.
4. P_i - the momenta of secondary particles.
5. θ_i - the angle of emission of secondary particles.
6. J - it was possible to estimate (visually) ionization produced by secondary particles in the gas of cloud chamber.

Thus, the information obtained for every shower is rather complete for the detailed analysis of the picture of the collision. Starting from 1958 the installation has been in operation for about 6000 hours. Up to day more than 100 showers were recorded produced at interactions of particles (with the energy > 100 GeV) with the nuclei of atoms of target or with the nuclei of atoms of chamber walls. By the present moment about 80 showers were treated, from which 60 showers were generated in the LiH target and 20 showers out of target. 20 showers are under treating now.

The samples of pictures for several showers are given in Fig.2.

The analysis of photographs received by means of the upper cloud chamber has shown that about half of the total number of showers were generated by neutral particles. This fact allows to conclude that in our conditions generating particles in the overwhelming majority of cases were nucleons.

Some other authors also have come to the same conclusions. This circumstance and the small atomic number of nucleus of target (LiH) suggest that registered showers were produced in nucleon-nucleon collisions. This point of view was taken as the basic in our further interpretation of the obtained data.

The data obtained at the first stages of the investigation have shown the existence of asymmetrical showers in the C-system of colliding nucleons. This fact has been con-

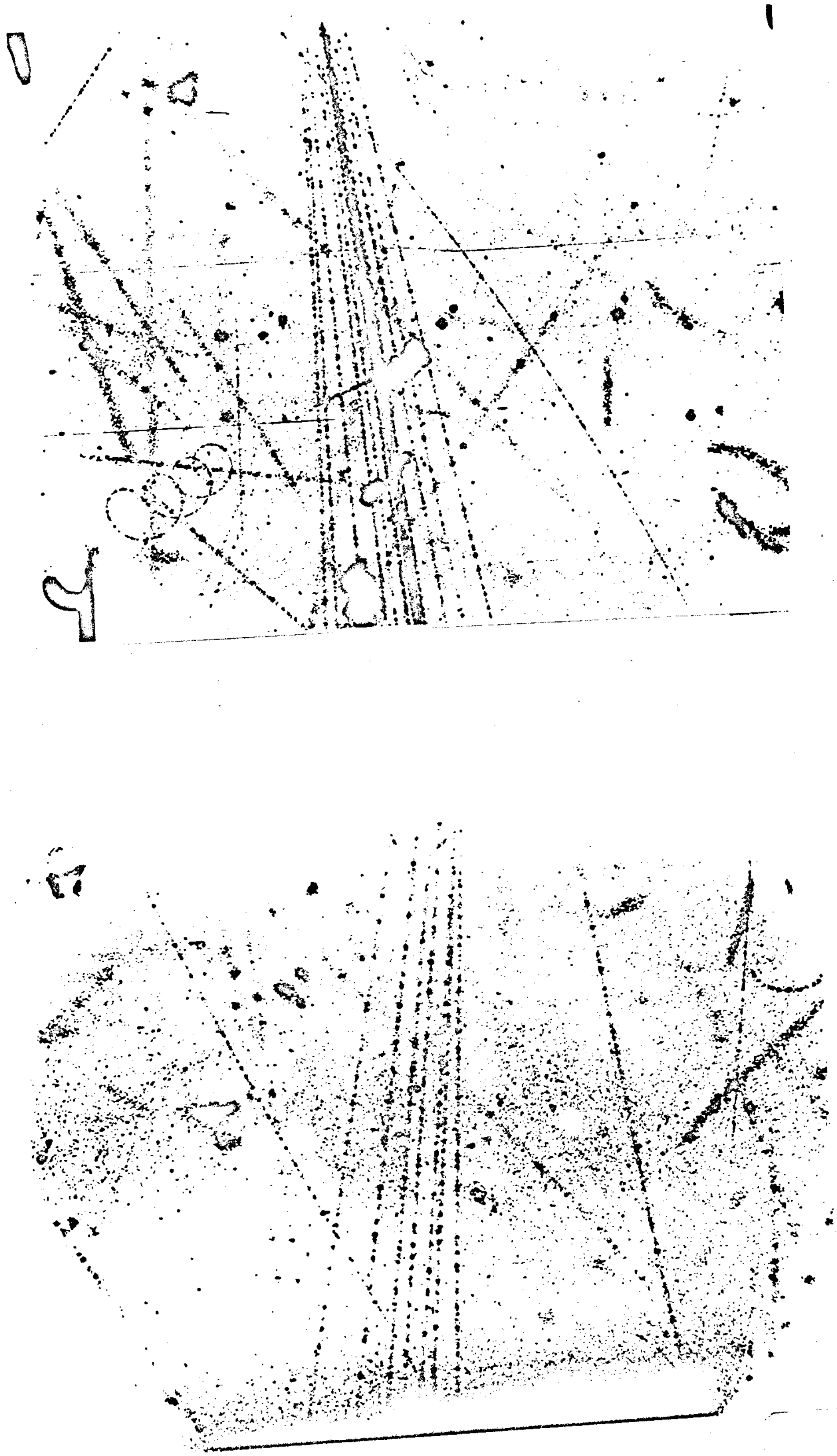

Fig 2

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firmed now with greater experimental material. Fig.3 shows pictures of the angular distribution in the C-system for some showers obtained.

It is seen from the obtained data, that 28 showers out of 46 proved to be more or less symmetrical, and 18 have considerably strong asymmetry.x)

The obtained data were analysed both by ordinary statistical methods and by Monte Karlo method. The analysis has shown, that the probability to find such number of asymmetrical showersxxx) does not exceed several per cent.

As it was shown before two inelasticity coefficientsxx) are important for characterizing each nucleon-nucleon interaction - the inelasticity coefficient in the laboratory system $K^{lab.}$ (i.e., in the system connected with the target -nucleon) and the inelasticity coefficient in the system connected with the incident nucleon $K^{mir.}$ ("mirror" system).

The average values of inelasticity coefficients K^{lab} and K^{mir} obtained from many showers are naturally equal one to another $\bar{K}^{lab} = \bar{K}^{mir}$. But they are considerably different for a large part of individual interactions as it may be seen from Fig.4.

In Fig.4 the values of K^{lab} are given against K^{mir} for 46 showers. The ordinate axis is used for K^{lab}, the abscissa for K^{mir}. Each symmetrical shower is represented by a point; a case of "forward" asymmetry by a sign ▲ ; and a case of "backward" asymmetry by a sign ▼ .

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x) For the rest of 14 showers only lower value of energy Eo was determined, and therefore we can not carry out the transition to the C-system for these showers with the sufficient accuracy.

xx) The inelasticity coefficient is the ratio of energy, transferred to all secondary π -mesons to the energy of primary nucleon

$$K = \frac{1.5 \sum E_{\pi^{\pm}}}{E_0}$$

xxx) owing to fluctuations in the angular distribution of charge and neutral π - mesons

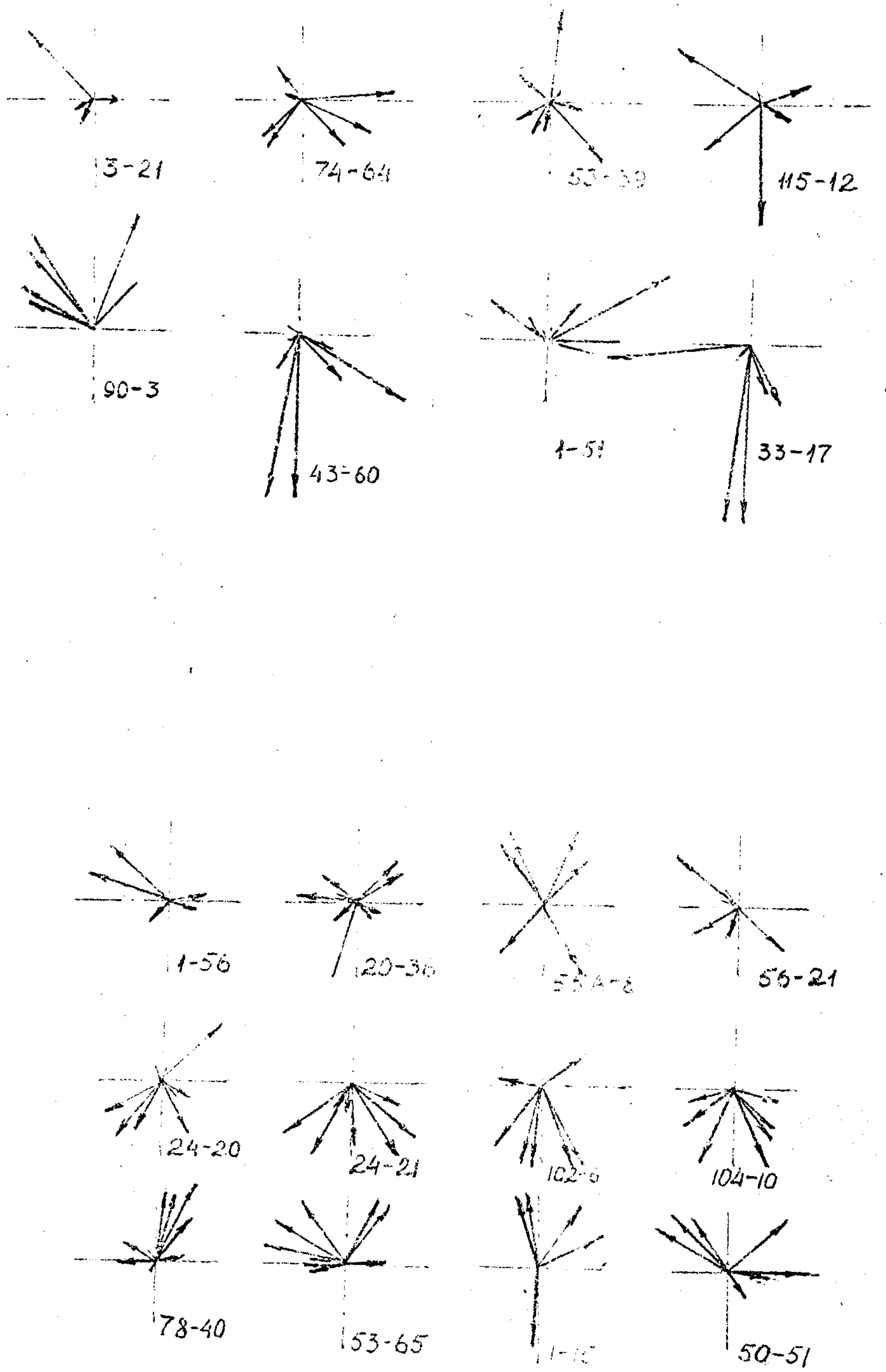

Fig 3

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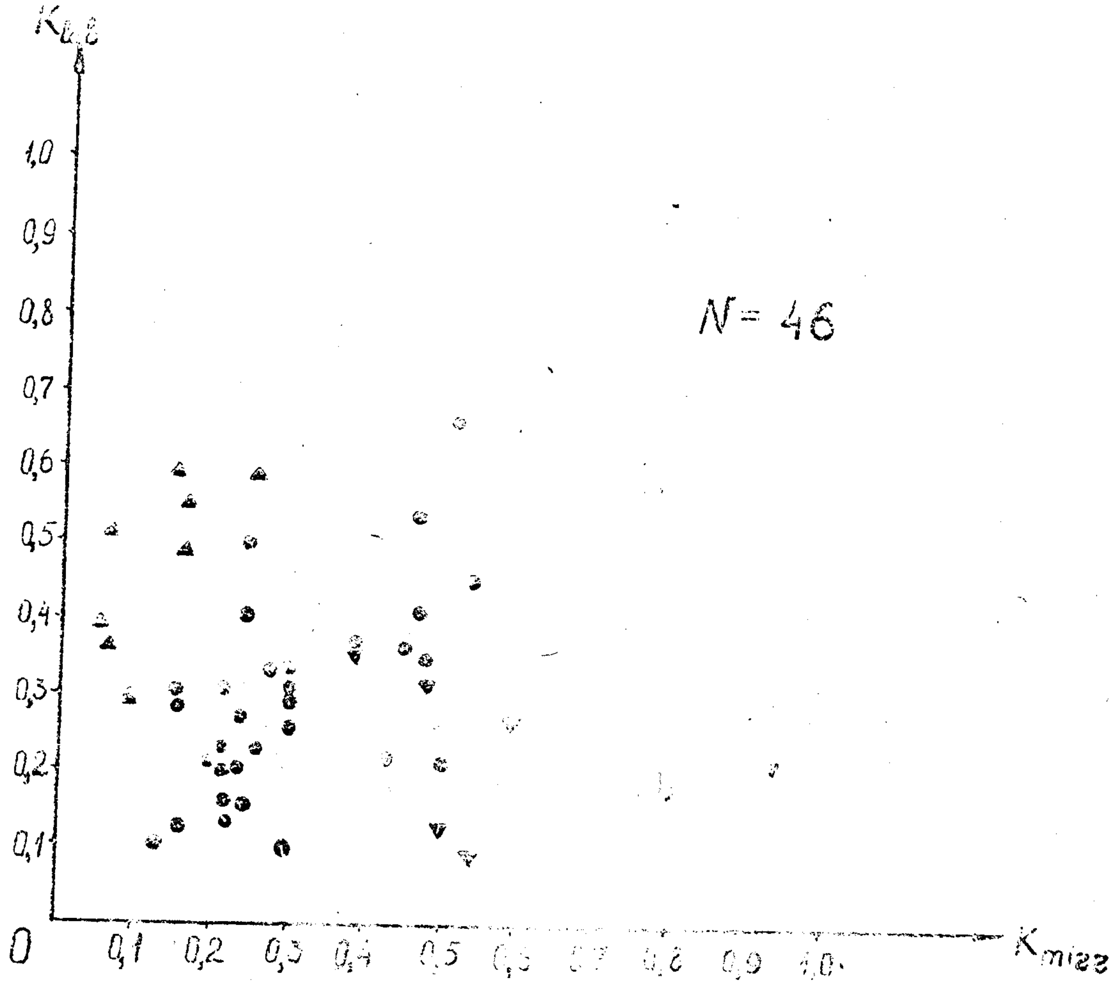

Fig 4

This figure shows ... closely connected with the inelasticity coefficient values characterizing the given collision of two nucleons.

This fact allows to divide nucleon-nucleon interactions into three types:

1. Symmetrical showers with nearly equal and small values of both inelasticity coefficients;
2. Asymmetrical showers for which one of the inelasticity coefficients is considerably greater than the other;
3. Symmetrical showers with great values of the both inelasticity coefficients.

At dividing nucleon-nucleon interactions into these three types we consider that the internal structure of nucleons is reflected. Showers of the first type can be interpreted as interactions of the periphery of one nucleon with the periphery of the other; showers of the second type - as interactions of the periphery of one nucleon with the central part of the other, and interactions of the third type - as interactions of central parts of both nucleons /2/.

Fig.5 gives the distribution of inelasticity coefficients x). The characteristic feature of this figure is the presence of maximum at the value of the inelasticity coefficient close to 0,25 (i.e. at the value which exceeded s slightly the ratio of masses π-meson and proton). This fact can be considered as indication on the definite separation of a π-meson in the structure of nucleon. Such interpretation was suggested before under the consideration of effective target mass, which take part in the interaction of nucleons. /3/

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x) The values of K^{lab} and K^{mir} were determined in the experiment from the practically independent data. Therefore the distributions of K^{lab} and K^{mir} are taken together for the increase of statistics.

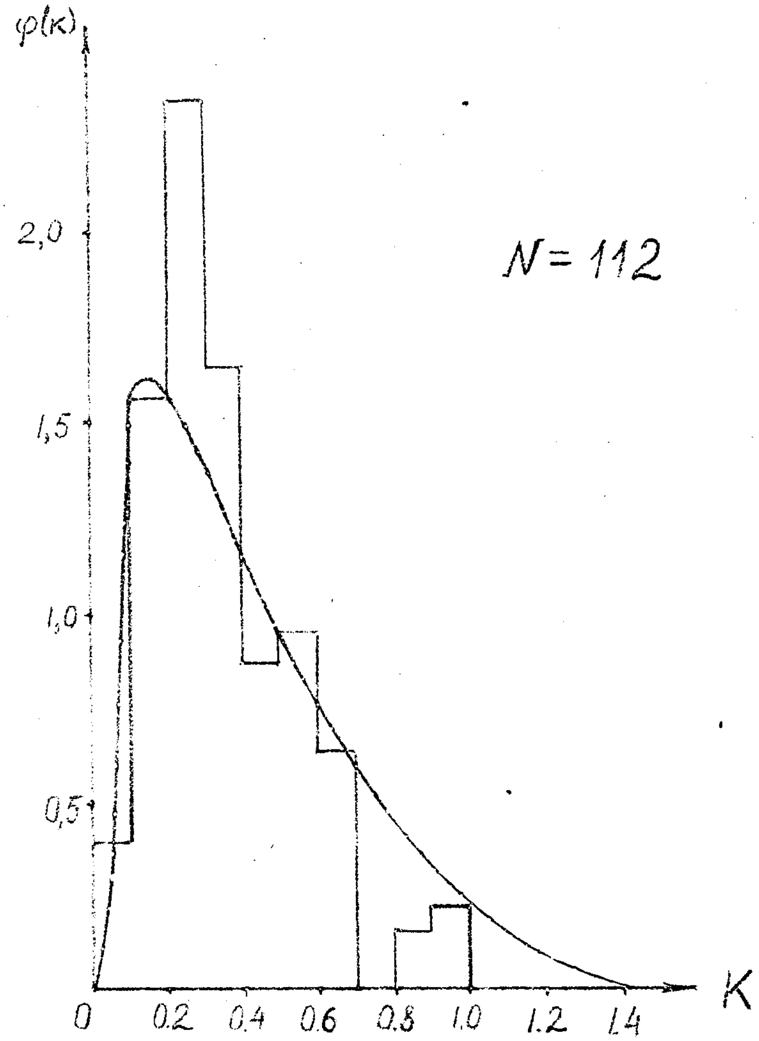


Fig 5

From the point of view of physics this fact can be interpreted also that the nucleon for some time $\Delta\tau \sim \frac{h}{\Delta E} \sim \frac{h}{\mu_\pi}$ is in the dissociated state with the isolated π-meson. The time of nucleons collision $\Delta t \sim \frac{h}{\gamma/\mu_\pi}$ is much less than $\Delta\tau$ at the energies of hundreds of Gev. This is why virtual - π-mesons can be considered as real particles.

One can try also to describe all these three types of nucleon-nucleon interactions from this point of view as the collision of these π-mesons (taking into account their inter-nucleon motion).

Further consideration is only of the illustrative character, it satisfactorily agrees with ours experimental results, but does not pretend to be more or less complete or successive and well theoretically grounded description of nucleon interaction process.

Let us denote the total energy of interacting π-mesons in dissociated nucleons by ω' and ω'', and by q', q'' - longitudinal components of their momenta in the rest system of the corresponding nucleon.

In such a consideration the energy transferred to π-mesons at the nucleons interaction is determined by energies $\mathcal{E}'$ and $\mathcal{E}''$ and momenta K', K'' of π-mesons in the C-system.

If an excited system with the mass-M, and Lorentz factor relatively the C-system γ_{MC} is formed in the collisions of nucleons, then

$$M\gamma_{MC} = \mathcal{E}' + \mathcal{E}''$$

(1) $$M\sqrt{\gamma_{MC}^2 - 1} = K' + K''$$

the values of M and γ_{MC} can be determined from the experimental data. It is easy to show, that

(2) $$M = 2\gamma_c \mu_{nucl} \cdot \sqrt{K_{lab} \cdot K_{miz}}$$

(3) $$\gamma_{MC} = \frac{K_{lab} + K_{miz}}{2\sqrt{K_{lab} \cdot K_{miz}}}$$

From the equations (1), (2), and (3) we can get

$$K_{miz} = \omega'' - q''$$

$$K_{lab} = \omega' - q'$$

i.e. each of the inelasticity coefficients in the considered model is determined by the internucleon motion of π-meson (in the system, in which the nucleon is at rest). It seems possible to select such a distribution function $F(\omega)$ which would satisfactorily describe the experimental distribution $\varphi(K)$ using the connection between K and ω and q, and assuming that the angular distribution of secondary π-mesons in the rest system of nucleon is isotropic.

If $F(\omega)$ is considered to be Planck's function at $T \sim \mu_{\pi}$ and $\omega \sim \mu_{\pi}$, then, as the calculations have shown, the theoretical curve (shown in Fig.5 by a solid line) is in a good agreement with the experimental inelasticity coefficients distribution.

From the function $F(\omega)$ one can receive some other characteristics of nucleon interactions, such as the distribution of mass of excited system M, distribution of values γ_{MC} and so on.

The calculated distributions of M and γ_{MC} have practically coincided with the experimental distributions in spite of the fact, that the form of function $F(\omega)$ is theoretically groundless. But one can hope that such considerations shall turn out to be useful at developing the theory of nucleon-nucleon collisions.

It is also interesting to consider the characteristics of nucleon-nucleon interactions proceeding from the assumption on the production of excited meson cloud (fire ball) in such interaction.

The mass of such meson cloud M, as it was pointed out above, is $M=2\gamma_c \mu_{nucl}\sqrt{K^{lab} \cdot K^{mir}}$. We see that M depends on the values of the both inelasticity coefficients. Usually, both inelasticity coefficients are considered to be equal not only on the average but also for individual cases. However, our experimental data have shown, as may be seen from the above, that such assumption is wrong and it is necessary to determine both K^{lab} and K^{mir} for the analysis of individual interactions.

If we assume that the angular distribution of π-mesons in the system of excited meson cloud is symmetrical, then it becomes possible to determine the velocity of the meson cloud (β_{MC}) and therefore the energies of π-mesons in this system.

The results of such determination of average energies of π-mesons $\overline{E}_{\pi M}$ performed for different primary energies and different types of interactions are given in the following table. /4,5,6/

Type of interaction	$p+\tilde{p}$	$p+p$		nucleon-nucleon		
E_0 Gev	2	6	9	100	300	500
$\overline{E}_{\pi M}$ Gev	0,40	0,35	0,34	0,44	0,46	0,38

It follows from this table, that the average π-meson energy is constant (within the limits of errors of measurements) in the wide interval of primary energies E_0. Hence, $M = 1{,}5 n_s \cdot \overline{E}_{\pi M}$, where n_s is the number of charged π-mesons generated in the given interaction. The dependence of n_s from $M = 2\gamma_c \beta_{nucl} \sqrt{K^{lab} \cdot K^{mir}}$ is presented in Fig.6.

Taking into account great errors in the determination of K^{lab} and K^{mir} for individual interactions and fluctuations in the distribution of mesons on the charge state, one can assume that the experimental points collimate quite well around a straight line.

From the equations for determining M given in the above it follows that $n_s \sim \sqrt{E_0}$, and it is in a good agreement with conclusions of the Heisenberg's theory on multiple meson production at high energies. The more accurate determination of the experimental data will show whether this conclusion is well grounded or not.

For the asymmetrical showers, for which $K^{lab} \neq K^{mir}$, as it is seen from the formula for the Lorentz factor of the excited meson cloud in the C-system γ_{MC}, the value

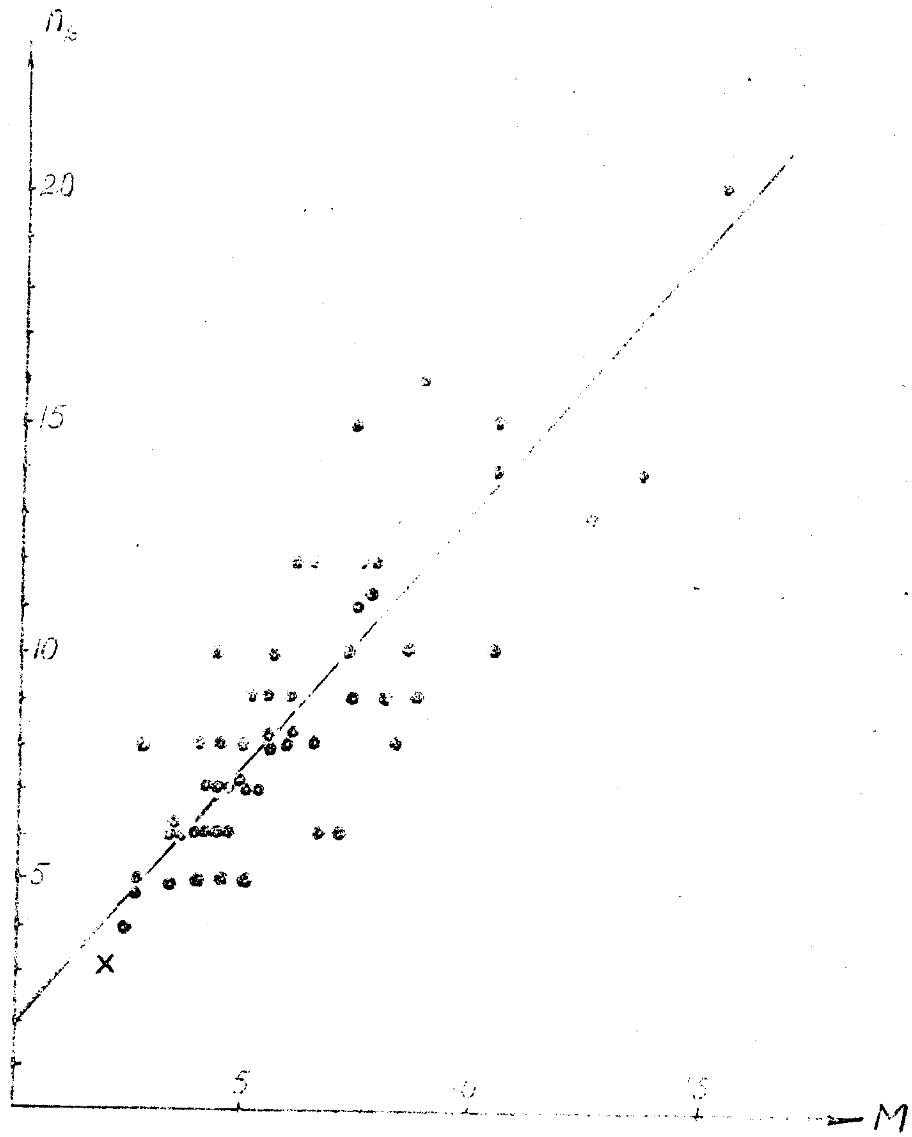


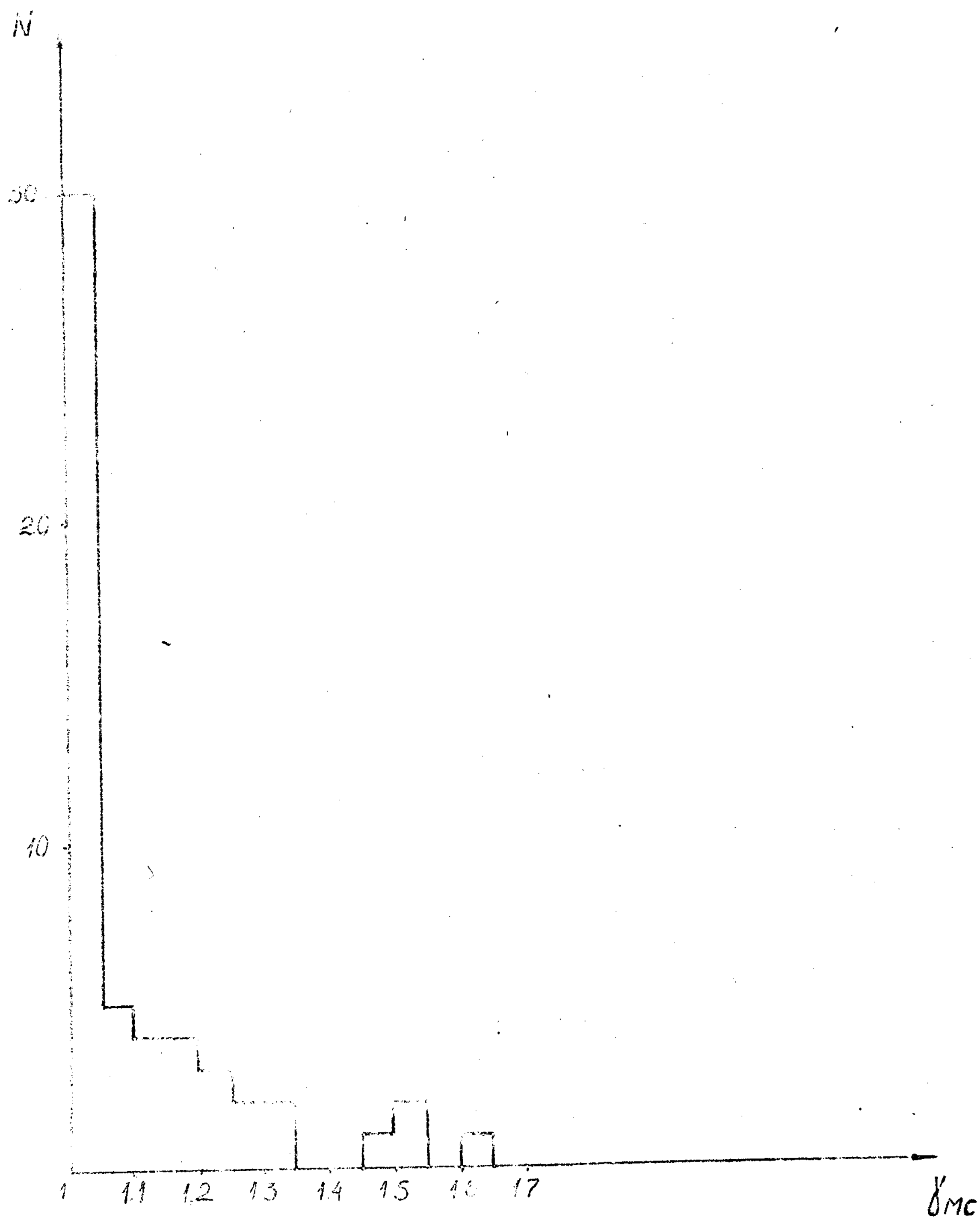
Fig. 5

of γ_{MC} differs from I. The asymmetry of showers can be explained by the motion of the excited meson cloud. The distribution of values γ_{MC} for analysed interactions is given in the Fig.7.

It should be emphasized that Lorentz factors of nucleons after the collision in the C-system are considerably greater than the Lorentz factor of excited meson cloud $\gamma_{nucl} > \gamma_{MC}$. Hence it follows, that meson cloud does not include the nucleons. This simplifies the analysis of the resultant picture. This fact is one of the essential advantages of the experiments at the energies of hundreds of Gev in comparison with the investigations at the energies available with the modern accelerators.

The existence of asymmetrical showers is a serious argument in favour of such meson cloud. The Lorentz factor of meson cloud was determined basing on the assumption that the angular distribution of π-mesons in the rest system of meson cloud is symmetrical. The obtained angular distribution, which is shown in fig.8, was found to be not only symmetrical, but isotropic also, as it could be expected. So far we considered the production only of a single cloud.

In general, in the nucleon-nucleon interactions two or more excited meson clouds can be produced. In such events the appearance of "two humpered" showers may be expected./9/ However, in our energy region the values of γ_{MC} are so close to 1, that the "two humpered" showers can not be realized. At the same time the angular distribution of π-mesons in C-system for showers of the third type (symmetrical showers with great values of the both inelasticity coefficients) shows distinctive anisotropy. It is seen in Fig.9. On the contrary, the angular distribution of π-mesons in the C-system for showers of the first type (symmetrical showers with nearly equal and small values of both inelasticity coefficients) is near to isotropic (fig.10). Such difference suggests, that in showers of the third type two excited meson clouds can be produced, but the energy of colliding nuc-



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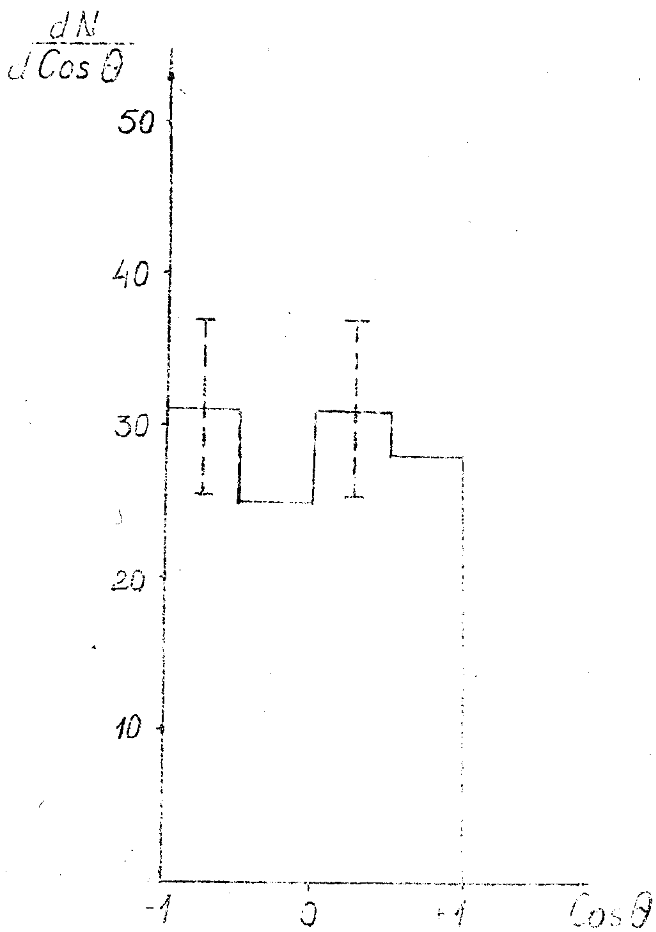

Fig 8

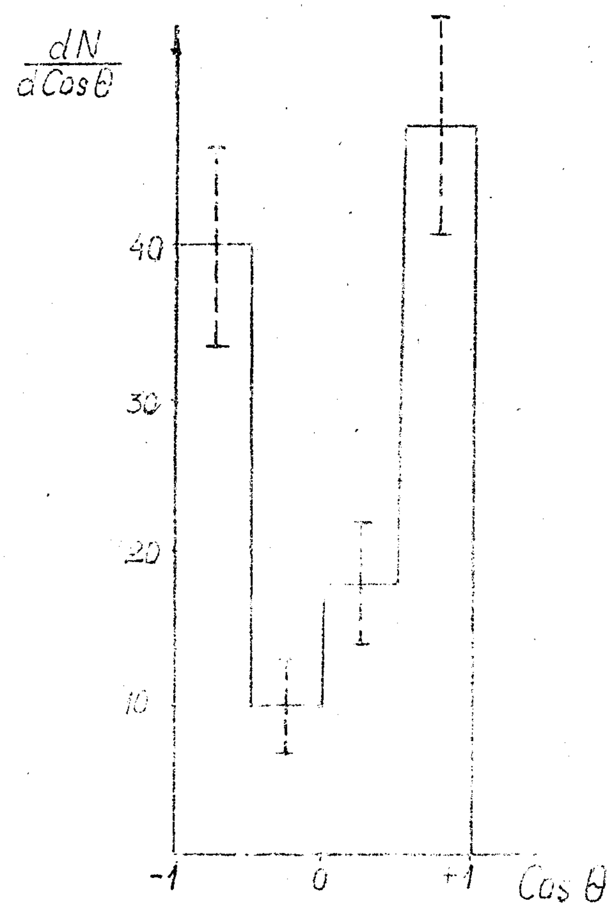

Fig 9

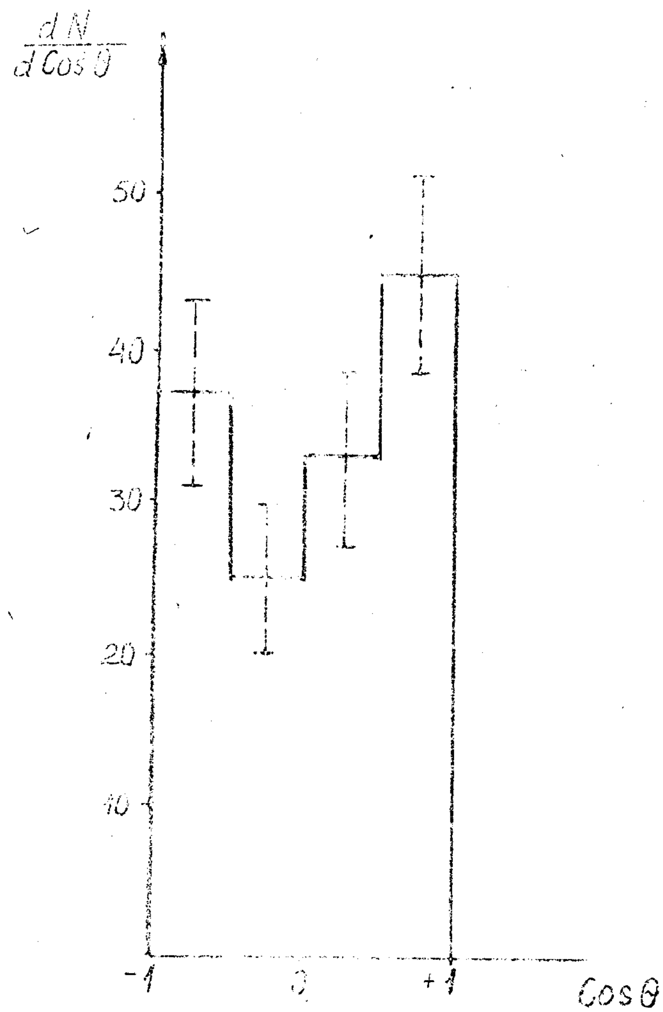

Fig 10

leons is not sufficient for separation of these clouds.

From our experimental data one can determine the values of the transverse momenta of shower particles. It was found that the average values of $\overline{p}_\perp$ are equal to 0,3÷0,4 Gev/c and the transverse momenta are independent from the values of M. Hence, it follows, that the disintegration of the excited system takes place at the same temperature T which is independent from M. The distribution of transverse momenta of the shower particles is given in Fig.11. Theoretical values of $p_\perp$ for the one-dimensional version of the hydrodinamical theory /7/ are plotted by a solid curve. Experimental and theoretical distributions are in a good agreement at $T=\mu_\pi$.

The distribution of total momenta of π-mesons in the system, where the angular distribution of mesons is symmetrical (i.e. M-system), is presented in the Fig.12. The experimental distribution was approximated by the Planck's function[x]:

$$N(p)dp = \frac{p^2 dp}{\mu_\pi^3} \frac{z^3}{F(z)} \left[e^{z\sqrt{(p/\mu)^2+1}} - 1 \right]^{-1}$$

where

$$z = \frac{\mu_\pi}{T}; \qquad F(z) = z^2 \sum_{m=0}^{\infty} \frac{K_2 \left[z(1+m) \right]}{1+m}$$

K_2-modificated Bessel's function of the second type. As it is seen from Fig.12, the best agreement with the experiment at $T=\mu_\pi$ as well as for the distributions of $p_\perp$.

The probable value of the π-meson momentum is equal $p_{prob}=2\mu_\pi$, the average value is equal $\overline{p}=3\mu_\pi$. The average value of π-meson energy is equal $\overline{E}_\pi=3,3\mu_\pi$. The fact that the momenta distribution in the M-system is satisfactorily described by the Planck's function testifies once more in favour of existence of the single meson cloud.

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x) Such approximation was used in the article /8/.

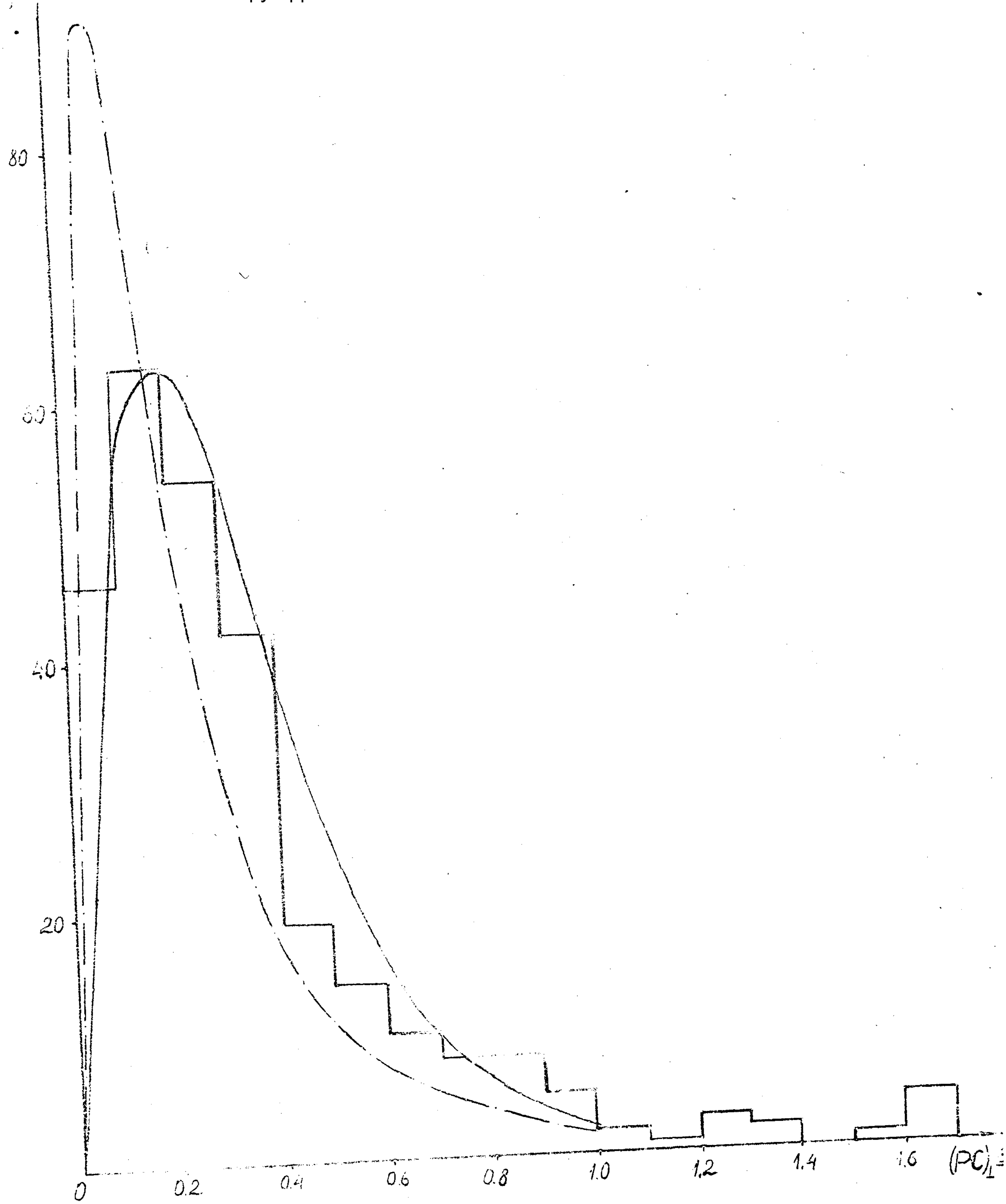

Fig 11

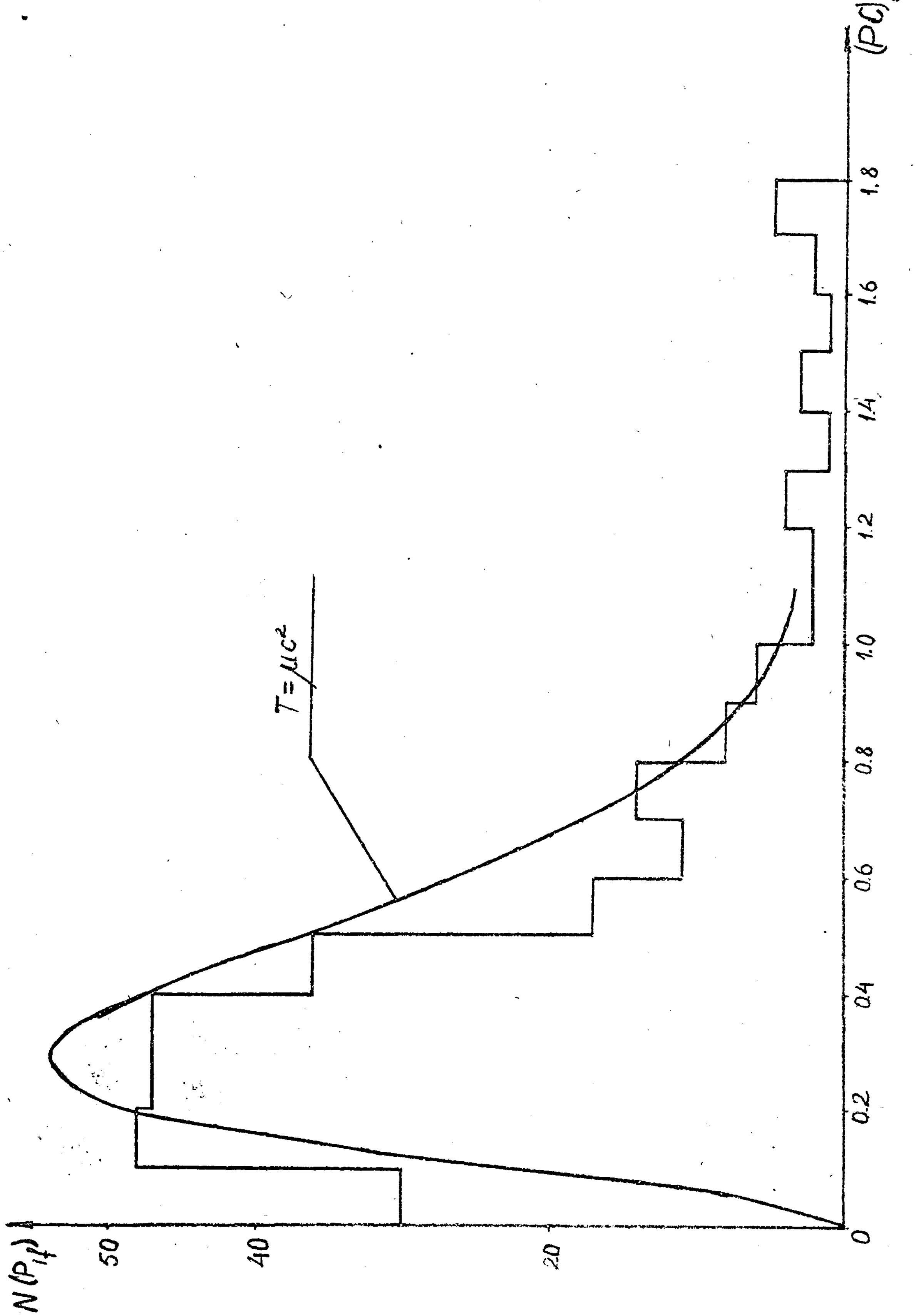

Fig 12

CONCLUSIONS

The analysis of data, obtained at studying nucleon-nucleon interactions at the energies of hundreds of Gev shows, that these interactions may be interpreted on the basis of a rough-model consideration on the nucleon structure.

At the same time these data suggested that at the collision of nucleons with such energies the excited meson cloud was, apparently, produced, which did not include the colliding nucleons. In general, the produced cloud moves with relatively small velocity in the C-system. The excited cloud disintegrates when its temperature attains the value $T \sim \mu_\pi$. The disintegration of the excited meson cloud is isotropic (in the system of coordinates connected with the cloud itself). The energy distribution of mesons, apparently, is similar to the emission spectrum of the absolute black body.

One can hope, that the further analysis of obtained data and collecting new results will allow us not only to confirm once more these conclusions, but to clear up the questions on the application of model considerations, on the role of nucleon's core, on the degree of the virtuality of the peripherical π-mesons, on the production of excited meson clouds and etc.

In any case, it is proved now that the continuation of studying nucleon-nucleon interactions in cosmic rays at the energies of hundreds of Gev gives the great possibility for the clearing up the peculiarities of the internal field of the nucleons.

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